A Beam-Steerer Using Reconfigurable PBG Ground Plane

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Abstract — Phased arrays with reduced cost and increased power handling capability are important for commercial applications. In this paper, we demonstrate beam-steering arrays using reconfigurable periodic structures in the ground plane without solid-state phase shifters. A linearly discrete beam-steering of 35° in steps of approximately 6° has been achieved at a fixed frequency of 5.6 GHz. The main beam power varied less than 2 dB over the whole range of beam-steering. A frequency-dependent beam-steering of 15° is also achieved from 5 GHz to 6 GHz.

I. INTRODUCTION

Electronic beam-steering finds increasing use in areas such as reconfigurable wireless and satellite communication networks, smart weapons, automobile and airplane radar. Beam-steering is achieved by linearly varying the phase between adjacent elements of an antenna array [1]. The phase variation can be achieved in one of two ways: by changing the operating frequency [2], which is not desirable in some cases, or by using electronic phase shifters and operating the array at a fixed frequency [3,4]. However this usually requires many expensive phase shifters and the number of phase shifters scales with the number of antennas in the array. In addition, an electronic phase-shifter along the transmission line may be a limiting factor as to the power handling capability and nonlinearity of the antenna. In this work, we demonstrate the feasibility of using reconfigurable photonic band gaps (PBG) on ground plane to eliminate phase shifters.

Photonic band gaps are periodic structures [5-7] on the ground plane that have been shown to produce frequency dependent amplitude characteristics on the microstrip circuits, and have been utilized as filters and resonators for various applications. However, the phase characteristics of the PBG have not been utilized. This paper presents a fixed-frequency beam-steering array based on reconfigurable PBG ground planes.

II. DESIGN AND MEASUREMENTS

A. APPROACH

It was shown [8] that PBG ground planes in addition to producing a stopband, also changes the propagation constant (β) in its passband. At the edge of the passband, the value of β is almost double that of a normal microstrip line. This in turn implies it is a slow-wave structure with a wave velocity that is half of the normal microstrip line. If there is a way to reconfigure the PBG ground plane, in other words, if the number of PBG periods on the ground plane are varied somehow, a true-time delay line will be formed. A phase shifting structure and subsequently a phased-array can be designed using this characteristic. The antenna should operate in the passband (preferably at the passband edge for maximum phase shifting) so that the signal does not get attenuated before reaching the antenna. This idea forms the basis for our approach and we demonstrate its feasibility by using conductive tape to vary the number of PBG periods. The conductive tape is used to imitate PIN-diode [9] or microelectro-mechanical system (MEMS) [10] switches turning on and off.

B. PHASE SHIFTER

A 50-Ω microstrip line with a length of 95 mm was fabricated. Eight periods of PBG holes in three columns for a stopband frequency of 10 GHz was etched in the ground plane, as shown in Fig. 1. The case shown in the figure corresponds to 6 PBG periods formed by covering two periods with conductive tape or PIN-diode switches. An RT Duroid board with $\varepsilon_r = 2.2$ and a thickness of 0.508 mm was used. The PBG periods are 10.9 mm and the radius of the holes is 2.7 mm. The equation for designing the PBG ground plane is given in [6]. The number of PBG periods was varied by short-circuiting the holes and the electrical delay (τ) of the line was measured on an HP8510C network analyzer as shown in Fig. 2. The electrical delay is seen to increase linearly with the number of PBG periods.
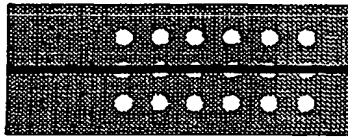
Figure 1. The microstrip line with PBG ground plane. The case shown here corresponds to 6 PBG periods formed by covering two periods with conductive tape or diode switches.
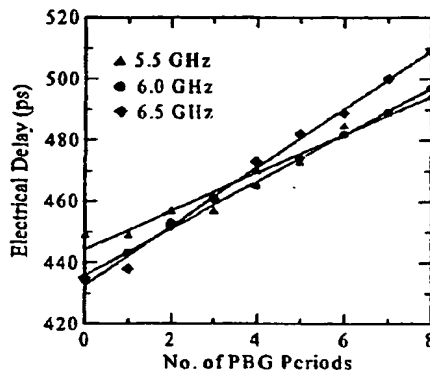

Figure 2. Electrical delay for a 50-Ω microstrip line with a length of 95 mm as a function of the number of PBG periods on the ground plane.
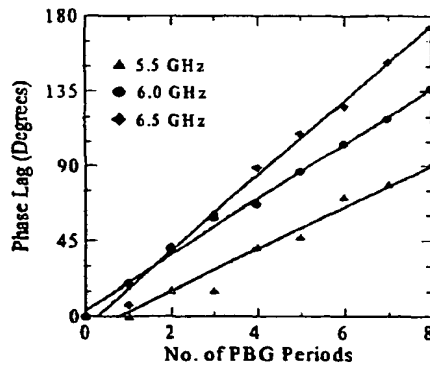

Figure 3. Phase of a 50-Ω microstrip line with a length of 95 mm as a function of the number of PBG periods on the ground plane. The phase is normalized with respect to the phase of a line with no PBG holes.

The phase response of the line can be calculated from the measured electrical delay. For the design of phased array antennas, the parameter of interest is the change in phase with number of PBG periods. Therefore, the relative phase shift of the PBG line was calculated using the following formula:

$$ Phase\ Lag = \frac{\tau_{PBG,n} - \tau_{N,m}}{(1/f)} \times 360° \qquad (1) $$

where f is the frequency, $\tau_{PBG,n}$ and $\tau_{N,m}$ correspond to the electrical delay of a PBG microstrip line with n periods and a normal microstrip line, respectively. The resulting phase lag curves are presented in Fig. 3. It is seen that the phase lag increases linearly with the number of PBG periods, which is desirable for designing phased-array antennas.

C. PHASED-ARRAY ANTENNA

A four-element microstrip patch-antenna array was designed to operate at 5.6 GHz. An RT Duroid board with $\varepsilon_r = 2.2$ and a thickness of 0.508 mm was used. A schematic of the array is shown in Fig. 4(a). The patch antenna dimensions are 15.1 × 18.2 mm. The 50-Ω feedlines are centered at 4.8 mm from the edges of the 15.1-mm sides of the antenna. The element spacing is 20 mm. Three columns of 18 PBG periods per column were etched on the ground plane under each of the lines. The maximum phase lag between adjacent antennas is obtained when the PBG periods are configured such that 0, 6, 12 and 18 (0-6-12-18) periods are formed under the four lines, respectively. Fig. 4(a) shows the case 0-1-2-3 as an example. The design dimensions are shown in Fig. 4(b).
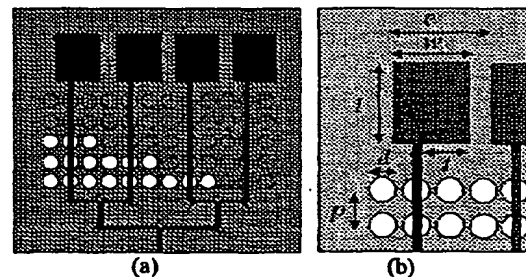

(a)   (b)

Figure 4. (a) The 4-element patch-antenna array with the PBG holes on the ground plane. Only five PBG periods are shown here. The case shown in the figure corresponds to 0-1-2-3 PBG periods on the ground plane. (b) Schematic showing antenna and PBG dimensions. ($w = 15.1$ mm, $l = 18.2$ mm, $t = 11$ mm, $d = 5.4$ mm, $p = 10.9$ mm and $e = 20$ mm).

To find the frequency of maximum beam-steering, the main-beam angle and the transmitted power at that angle for a range of frequencies were measured. The phased-array was used as the transmitting antenna and a 2-18 GHz horn was used as the receiving antenna to measure the beam-steering

patterns. The signal was supplied by a precision HP8350B microwave source and the received power was measured with an HP8564E spectrum analyzer. The measured beam-steering angles and the peak powers are shown in Fig. 5. It is seen that maximum beam-steering angle is obtained at 5.9 GHz, and the maximum power is obtained at 5.3 GHz. Both the beam-steering angle and the maximum power obtained decrease quickly above 6 GHz. This is due to the fact that 6 GHz is at the band edge of stopband for the 18-period PBG line. Therefore, 5.6-GHz was chosen as compromise between maximum beam-steering angle and the maximum transmitting power.
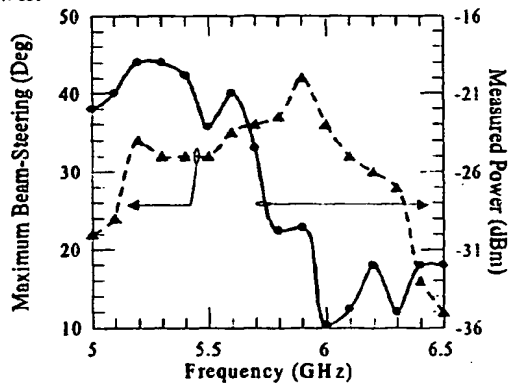
Figure 5. Measured beam-steering and peak power of the array for the configuration of 0-6-12-18 PBG periods.
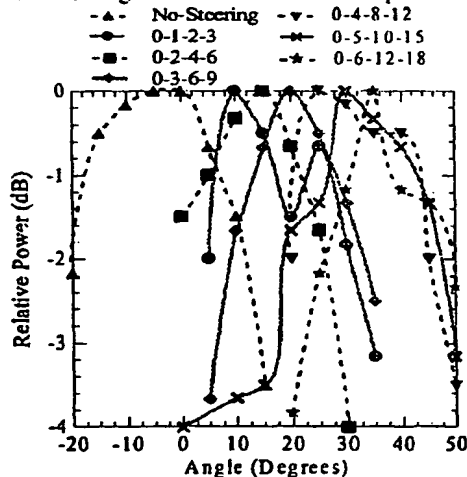
Figure 6. Measured main-beam patterns for the different ground-plane configurations. The array steers in increments of approximately 6°. Full patterns from -90° to +90° are measured. Only the peaks of the steered patterns are shown here.
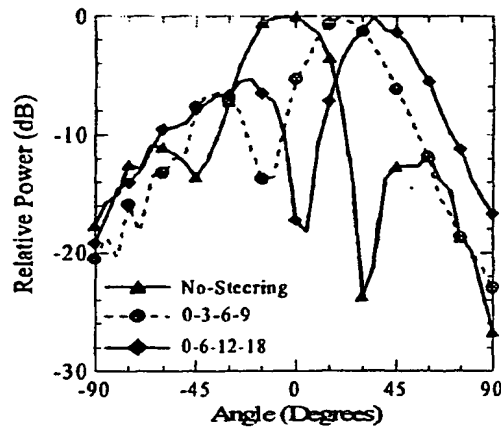
Figure 7. Measured beam-steering patterns. Only three of the seven different full radiation patterns possible with the implemented antenna are shown for clarity.
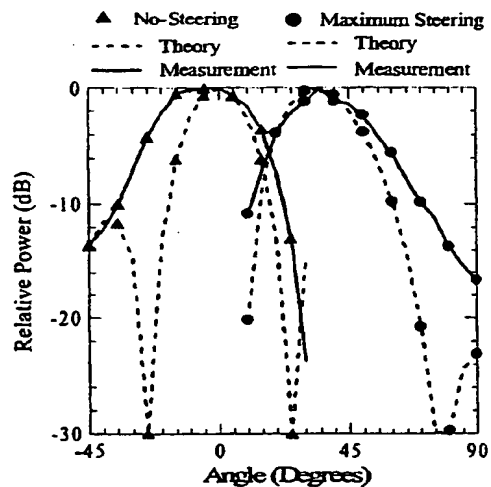
Figure 8. Comparison of theoretical and measured antenna patterns for the no-steering and maximum beam-steering cases.

The discrete beam-steering patterns are obtained by covering a varying number of PBG periods with conductive tape, as shown in Fig. 6. Only the beam-peaks are shown for clarity. The different patterns have individually been normalized, nonetheless the relative peak powers of the different steering patterns varied by less than 2 dB. The beam-steering angle varies linearly as the number of PBG periods is varied and a maximum beam-steering of 35° is obtained. As the array is one-dimensional, only the H-plane beam

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steering is obtained. Two-dimensional beam steering is possible with a 2-D array.

The measured beam-steering patterns are shown in Fig. 7 over ±90°. It is seen that the shapes of steered patterns are similar for different ground-plane configurations. The measured patterns are compared with the simulation results in Fig. 8. The theoretical patterns are obtained with the phased-array factors and the patch antenna pattern. It is seen that there is a good agreement between the two.

The H-plane co- and cross-polarization patterns are compared in Fig. 9. At the main beam, the polarization ratio is about 12 dB. Same measurements were repeated for all the steered patterns and the co-pol to cross-pol ratios better than 12 dB at the main beams were maintained as the beams were steered.
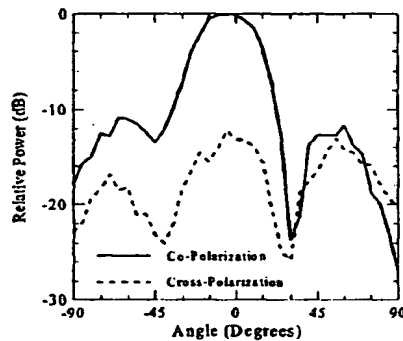

Figure 9. Measured H-plane co- and cross-pol patterns at 5.6 GHz.
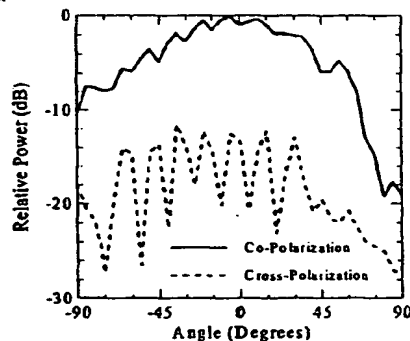

Figure 10. Measured E-plane co- and cross-pol patterns at 5.6 GHz.

The E-plane co- and cross-polarization patterns are compared in Fig. 10. Again a good polarization ratio is obtained. The measured and theoretical directivities of the array are 13.8 and 11.5, respectively. The directivity can be increased by adding more array elements.

III. CONCLUSIONS AND FUTURE WORK

A novel approach to implement phased-arrays has been proposed and implemented. A discrete beam-steering in linear steps of approximately 6° up to 35° has been achieved.

The immediate future work in this project is to implement the reconfigurable photonic bandgaps using PIN diode switches. We also intend to implement MEMS switch-based [10] arrays at millimeterwave frequencies where the size, cost and loss reduction benefits of this approach will be magnified.

ACKNOWLEDGEMENT

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